EFFECT OF WATERSHED SUBDIVISION ON SWAT FLOW, SEDIMENT, AND NUTRIENT PREDICTIONS[1]

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ABSTRACT: The size, scale, and number of subwatersheds can affect a watershed modeling process and subsequent results. The objective of this study was to determine the appropriate level of subwatershed division for simulating flow, sediment, and nutrients over 30 years for four Iowa watersheds ranging in size from 2,000 to 18,000 km[2] with the Soil and Water Assessment Tool (SWAT) model. The results of the analysis indicated that variation in the total number of subwatersheds had very little effect on streamflow. However, the opposite result was found for sediment, nitrate, and inorganic P; the optimal threshold subwatershed sizes, relative to the total drainage area for each watershed, required to adequately predict these three indicators were found to be around 3, 2, and 5 percent, respectively. Decreasing the size of the subwatersheds below these threshold levels does not significantly affect the predicted levels of these environmental indicators. These threshold subwatershed sizes can be used to optimize input data preparation requirements for SWAT analyses of other watersheds, especially those within a similar size range. The fact that different thresholds emerged for the different indicators also indicates the need for SWAT users to assess which indicators should have the highest priority in their analyses.
(KEY TERMS: modeling; flow; sediment; nutrients; watershed subdivision; sensitivity analysis.)

INTRODUCTION

It is common practice to subdivide a watershed into smaller areas or subwatersheds for modeling purposes. Each subwatershed is assumed homogeneous with parameters representative of the entire subwatershed. However, the size of a subwatershed affects the homogeneity assumption because larger subwatersheds are more likely to have variable conditions. An increase in the number of subwatersheds definitely increases the input data preparation effort and the subsequent computational evaluation. Similarly, a decrease in the number of subwatersheds could affect the simulation results. Therefore, an appropriate subwatershed scale should be identified that can efficiently and adequately simulate the behavior of a watershed.

The impact of subwatershed scaling upon a watershed simulation is directly related to the sources of heterogeneity (Arnold *et al.,* 1998), which include the channel network, subwatershed topography, soils, land use, and climate inputs. Goodrich (1992) studied how basin scales can affect the characterization of geometric properties. He showed that changes in drainage density affect the accuracy of runoff predictions. Mamillapalli *et al.* (1996) found that improved accuracy of flow predictions with the Soil and Water Assessment Tool (SWAT) model (Arnold *et al.,* 1998; Srinivasan *et al.,* 1998; Neitsch *et al.,* 2001a) for the 4,297 square kilometer (km[2]) Bosque River Watershed in central Texas resulted from increasing the number of subwatersheds and/or the number of Hydrologic Response Units (HRUs). They did not present any method for determining the optimal subwatershed/HRU configuration for a watershed. Bingner *et al.* (1997) found that predicted sediment yield with

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SWAT for the 21.3 km^2 Goodwin Creek Watershed in northern Mississippi was sensitive to the number of simulated subwatersheds but that the predicted surface runoff was insensitive to subwatershed delineation. They also found that sensitivity analyses should be conducted on land use, overland slope, and slope length for different subdivisions to find the appropriate number of subwatersheds required for modeling a watershed. They emphasized that additional research is necessary to develop more universal criteria and that such criteria could be difficult to determine. Similar to Binger *et al.* (1997), FitzHugh and MacKay (2000) found that SWAT streamflow estimates were relatively insensitive to different combinations of subwatershed and HRU delineations for the 59.6 km^2 Pheasant Branch Watershed in central Wisconsin. Predicted upland sediment losses did vary in response to subwatershed and HRU delineations, but the ultimate sediment loads estimated to leave the watershed changed little, due to the watershed being "transport limited." They present further insights as to why changes in subwatershed and HRU areas had limited impact on the SWAT streamflow and sediment loss predictions.

In this study, the SWAT model was used to evaluate the impact of subwatershed scaling on the prediction of flow, sediment yield, and nutrient losses for four watersheds in Iowa. The objective is to develop a guideline for a threshold level of subdivision that will allow: (1) accurate flow, sediment yield, and nutrient predictions with SWAT; and (2) a reduction of input data preparation and subsequent computational evaluation efforts without significantly compromising simulation accuracy.

THE SWAT MODEL

SWAT is a basin scale, continuous time model that operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields in ungauged basins (Arnold *et al.,* 1998). The model is physically based, computationally efficient, and capable of continuous simulation over long time periods. Major model components include weather, hydrology, soil temperature, plant growth, nutrients, pesticides, and land management. Previous applications of SWAT have compared favorably with measured data for a variety of watershed scales (Srinivasan and Arnold, 1994; Rosenthal *et al.,* 1995; Arnold and Allen, 1996; Srinivasan *et al.,* 1998; Arnold *et al.,* 1999; Saleh *et al.,* 2000). Brief descriptions of some of the key model components are provided here. More detailed descriptions of the model components can be found in Arnold *et al.* (1998), Neitsch *et al.* (2001b), and Jha (2002).

In SWAT, a watershed is divided into multiple subwatersheds, which are then further subdivided into HRUs that consist of homogeneous land use, management, and soil characteristics. The HRUs represent percentages of the subwatershed area and are not identified spatially within a SWAT simulation. The water balance of each HRU in the watershed is represented by four storage volumes: snow, soil profile (0 to 2 meters), shallow aquifer (typically 2 to 20 meters), and deep aquifer (more than 20 meters). Flow, sediment, nutrient, and pesticide loadings from each HRU in a subwatershed are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet.

Three options exist in SWAT for estimating surface runoff from HRUs – combinations of daily or subhourly rainfall and the Natural Resources Conservation Service Curve Number (CN) method (Mockus, 1969) or the Green and Ampt method (Green and Ampt, 1911). Three methods for estimating potential evapotranspiration are also provided: Priestly-Taylor (Priestly and Taylor, 1972), Penman-Monteith (Monteith, 1965), and Hargreaves (Hargreaves *et al.,* 1985). The option is also provided for the user to estimate ET values outside of SWAT and then read them into the model for the simulation run. Sediment yield is calculated with the Modified Universal Soil Loss Equation (MUSLE) developed by Williams and Berndt (1977). Neitsch *et al.* (2001a) provide further details on input options.

Sediment Routing

The sediment routing model (Arnold *et al.,* 1995) consists of two components operating simultaneously: deposition and degradation. The deposition in the channel and floodplain from the subwatershed to the watershed outlet is based on the sediment particle settling velocity. The settling velocity is determined using Stoke's Law (Chow *et al.,* 1988) and is calculated as a function of particle diameter squared. The depth of fall through a routing reach is the product of settling velocity and reach travel time. The delivery ratio is estimated for each particle size as a linear function of fall velocity, travel time, and flow depth. Degradation in the channel is based on Bagnold's stream power concept (Bagnold, 1977; Williams, 1980).

Once the amount of deposition and degradation has been calculated, the final amount of sediment in the reach is determined by

$$Sed_{ch} = Sed_{ch,i} - Sed_{dep} + Sed_{deg} \tag{1}$$

where Sed_{ch} is the amount of suspended sediment in the reach (t), $Sed_{ch,i}$ is the amount of suspended sediment in the reach at the beginning of the time period (t), Sed_{dep} is the amount of sediment deposited in the reach segment (t), and Sed_{deg} is the amount of sediment reentrained in the reach segment (t). Finally, the amount of sediment transported out of the reach is calculated by

$$Sed_{out} = Sed_{ch} * \frac{V_{out}}{V_{ch}} \tag{2}$$

where Sed_{out} is the amount of sediment transported out of the reach, V_{out} is the volume of outflow during the time step (m³), and V_{ch} is the volume of water in the reach segment (m³). The volume of water in the segment (V_{ch}) is the product of the length of the segment (m), the cross-sectional area (m²), and the flow at a given depth (m).

Nutrient Cycling and Movement

The transformation and movement of nitrogen (N) and phosphorus (P) within an HRU are simulated in SWAT as a function of nutrient cycles consisting of several inorganic and organic pools. Losses of both N and P from the soil system in SWAT occur by crop uptake and in surface runoff in both the solution phase and on eroded sediment. Simulated losses of N can also occur in percolation below the root zone, in lateral subsurface flow (including tile drains), and by volatilization to the atmosphere. Movement of nitrate (NO_3-N) in surface runoff, lateral subsurface flow, and percolation is computed as the product of the average soil layer NO_3-N concentration and the volume of water in each flow pathway. The mass of soluble P predicted to be lost via surface runoff is determined as a function of the solution P concentration in the top 10 millimeters of soil, the surface runoff volume, and a partitioning factor. Movement of organic N or organic and inorganic P on eroded sediment is estimated with a loading function initially derived by McElroy *et al.* (1976) and later modified for individual runoff events by Williams and Hann (1978). Daily losses are computed with the loading function as a function of the nutrient concentration in the topsoil layer, the sediment yield, and an enrichment ratio.

WATERSHED DESCRIPTIONS AND SWAT INPUT DATA

Four watersheds located within Iowa (Figure 1) that vary in drainage size from just under 2,000 km² to almost 18,000 km² were selected for this study (Table 1). The watershed boundaries are based on one or more eight-digit watersheds as defined by the hydrologic unit code (HUC) developed by the U.S. Geological Survey (USGS). A complete description of the HUC classification scheme is given in Seaber *et al.* (1987).

Input Data

Land use, soil, and topography data required for simulating each watershed in SWAT were obtained from the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) package, Version 3 (USEPA, 2001). Land use categories available from BASINS are relatively simplistic (Table 2), with only one category for agricultural use (defined as "Agricultural Land-Generic") provided. An egregious error in the amount of land defined as Residential-Medium Density currently exists in BASINS for Watershed 1 (HUC 10230005 in Figure 1) as indicated in Table 2. No attempt to correct this error was made for this study because the main intent was to assess the sensitivity of SWAT to variations in subbasin and HRU delineations, rather than to estimate the water quality impacts of different practices in the watershed.

The soil data available in BASINS comes from the State Soil Geographic (STATSGO) database (NRCS, 1994), which contains soil maps at a 1:250,000 scale. Each STATSGO map unit consists of from 1 to 21 component soil (the exact spatial location of these component soils are not known within a given map unit). Each STATSGO map unit is linked to the Soil Interpretations Record attribute database that provides the proportionate extent of the component soils and soil layer properties. The STATSGO soil map units and associated layer data were used to characterize the simulated soils for the SWAT analyses.

Topographic information is provided in BASINS in the form of digital elevation model (DEM) data. The DEM data were used to generate variations in subwatershed configurations for the four watersheds using the ArcView interface for SWAT 2000 (AVSWAT), developed by Di Luzio *et al.* (2001), as described in the simulation methodology section. The minimum and maximum elevations determined for each watershed from the DEM data are given in Table 1.
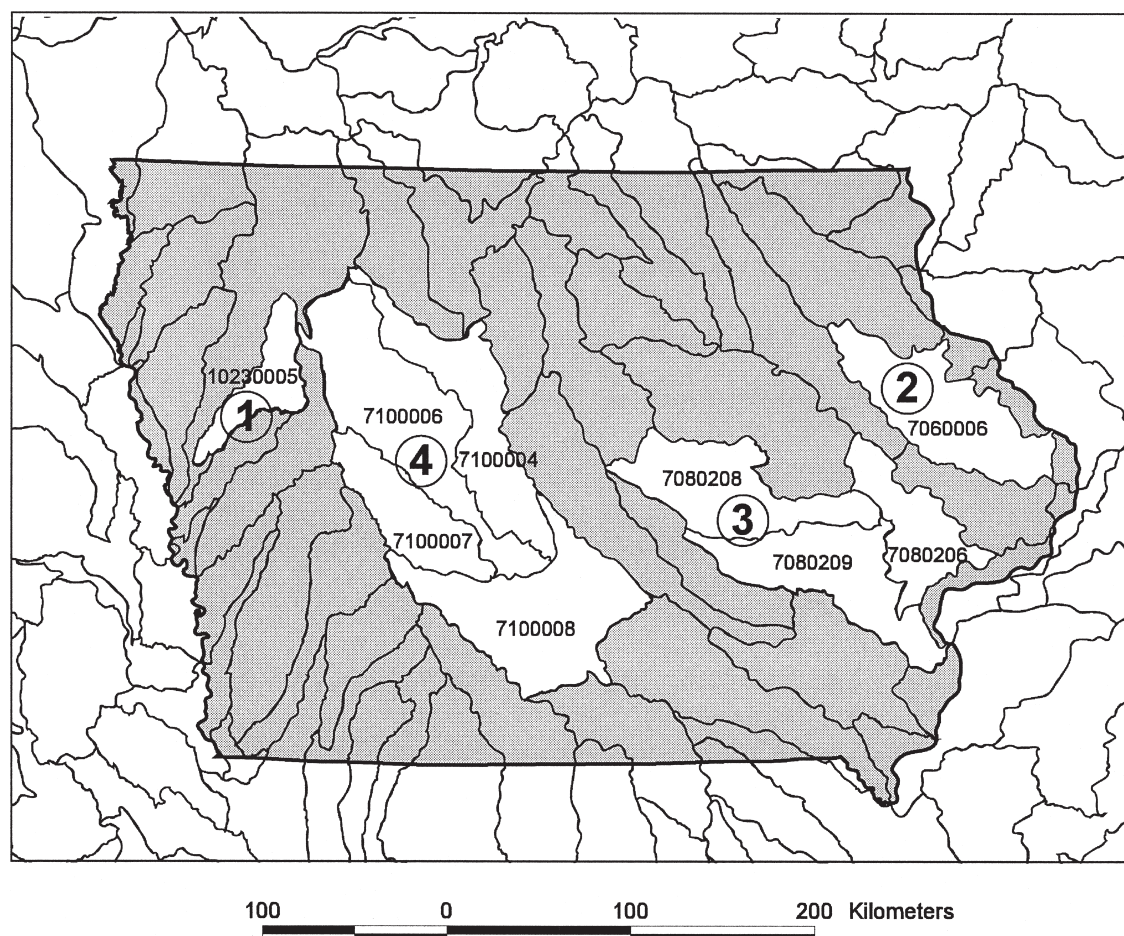
Figure 1. Locations of Watersheds 1 Through 4 Overlayed on the Boundaries of the Eight-Digit Hydrologic
Unit Watersheds That Comprise Each of the Four Watersheds (codes are shown
for the eight-digit watersheds within each of the four study watersheds).

TABLE 1. Watersheds Included in the Study.

Watershed	Drainage Area (km^2)	Minimum Elevation (m)	Maximum Elevation (m)
1	1,929	317	484
2	4,776	178	383
3	10,829	161	346
4	17,941	213	473

Two other key sets of inputs required for simulating the four watersheds in SWAT were climate and management data. The daily climate inputs consist of precipitation, maximum and minimum temperature, solar radiation, wind speed, and relative humidity; these were generated internally within SWAT for the 30-year period using monthly climate statistics provided for Iowa weather stations located in or near each watershed. The management operations required for the HRUs were determined by AVSWAT. These management operations consisted simply of planting, harvesting, and automatic fertilizer applications for the agricultural HRUs.

Other key options that were selected for these simulations included: (1) the Runoff Curve Number (CN) method for estimating surface runoff from precipitation, (2) the Penman-Monteith method for estimating potential evapotranspiration (ET) generation, (3) the variable storage method to simulate channel water routing, and (4) setting the channel dimensions to an inactive status.

SWAT VALIDATION

An initial validation exercise was performed for the Maquoketa River Watershed (Watershed 2 in Table 2 and Figure 1) as a check to ensure that SWAT could

TABLE 2. Land Use Characteristics for the Four Watersheds as Given in BASINS.

Legend	Land Use Type	Percentage of Total Watershed Area			
		Watershed 1	Watershed 2	Watershed 3	Watershed 4
AGRL	Agricultural Land – Generic	59.68	93.78	90.77	78.52
FRST	Forest – Mixed	-	-	-	0.01
ORCD	Orchard	-	-	0.01	0.01
RNGB	Range – Brush	-	-	-	0.06
RNGE	Range – Grasses	-	-	-	0.01
UCOM	Commercial	0.21	0.59	0.34	0.37
UIDU	Industrial	-	0.01	0.07	0.13
URMD	Residential – Medium Density	38.39*	0.12	1.06	12.96
UTRN	Transportation	0.06	0.16	0.38	0.38
WATR	Water	0.01	0.13	0.30	0.77
WETF	Wetlands – Forested	-	0.11	0.32	0.06
WETN	Wetlands – Nonforested	-	-	0.15	0.21

*The majority of this "residential land" should be defined as agricultural land (AGRL); the error was not corrected in BASINS 3.0 at the time of this study (R. Kinerson. 2002. personal communication. U.S. Environmental Protection Agency, Washington, D.C.).

produce reasonable flow estimates using the BASINS land use data for the relatively large watersheds included in this study. The validation was performed for 1981 to 1990 using historical daily precipitation and temperature data obtained for six climate stations (U.S. Department of Commerce, 1981-1990) located in or near the watershed (Figure 2). As shown in Figure 2, the watershed was subdivided into 25 subwatersheds for the validation simulation. Adjustments were made to some of the input parameters including the runoff curve numbers to achieve the best flow predictions.

Direct comparison between the simulated flows at the Watershed 2 outlet and measured data were not possible, due to a lack of observed flow data at the confluence of the Maquoketa and Mississippi rivers.
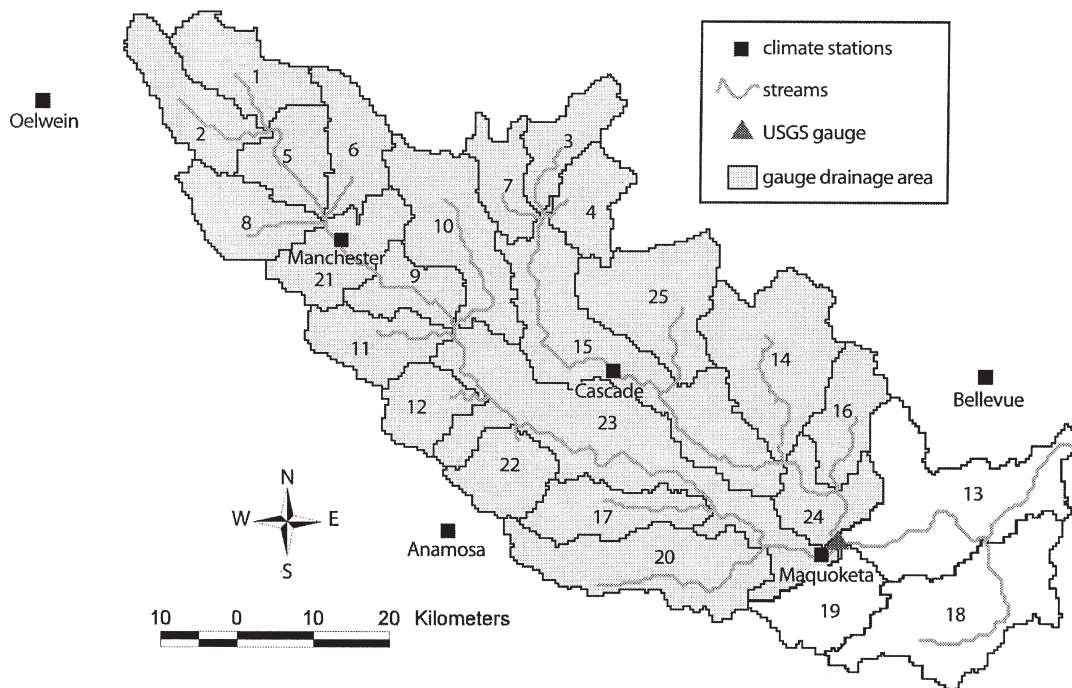

Figure 2. Climate Station Locations Relative to the 25 Subwatersheds That Were Used for the SWAT Validation of Watershed 7060006 (Maquoketa River Watershed) and the Location of the Streamflow Gage (USGS Station No. 05418500).

Flows measured at a USGS gauge (USGS Station # 05418500) on the Maquoketa River near Maquoketa, Iowa (Figure 2), were the nearest available that could be used for validating the simulated flows at the Watershed 2 outlet. The simulated flows at the outlet were compared to the measured flows at the USGS gauge by converting the flow rates to depths as follows:

$$D_o = (1000)\frac{Q_o}{A_o}(T) \qquad (3)$$

$$D_g = (1000)\frac{Q_g}{A_g}(T) \qquad (4)$$

where D_o is the simulated depth at the outlet and D_g is the measured depth at the USGS gauge (mm), Q_o is the flow rate at the outlet and Q_g is the flow rate at the USGS gauge (m^3/s), A_o is the watershed area that drains to the outlet and A_g is the watershed area that drains to the USGS gauge (m^2), and T is the time duration (s). It is assumed that the depth of the measured flow would not change over different portions of the watershed. Thus, the conversion of the simulated and measured flow rates to depths provides a direct means of comparison, even though the two drainage areas that contribute to the measured and simulated flows are different.

Figures 3 and 4 show comparisons of average daily and average monthly flows over the 10-year simulation period. In general, the predicted flows compared well with the projected measured values. There is a clear pattern of underprediction by SWAT for the flows simulated during the month of February, which may be due to an inaccurate depiction of snow melting occurring during that month. Slight overpredictions of the measured flows resulted for the majority of the rest of the year, as shown in both Figures 3 and 4. Resulting r^2 values for the average daily, average monthly, and average annual comparisons between the simulated and measured flows were 0.68, 0.78, and 0.65, respectively, indicating that the model accurately tracked the measured flows. These results confirm SWAT's ability to predict realistic flows using the relatively coarse land use data available from BASINS for the watersheds considered in this study.

SIMULATION METHODOLOGY FOR ASSESSING SENSITIVITY OF SUBWATERSHED DIVISIONS

A subwatershed is delineated for SWAT by estimating the overland slope using the neighborhood technique (Srinivasan and Engel, 1991) for each grid. Once the threshold drainage area (minimum drainage area required to form the origin of a stream) is
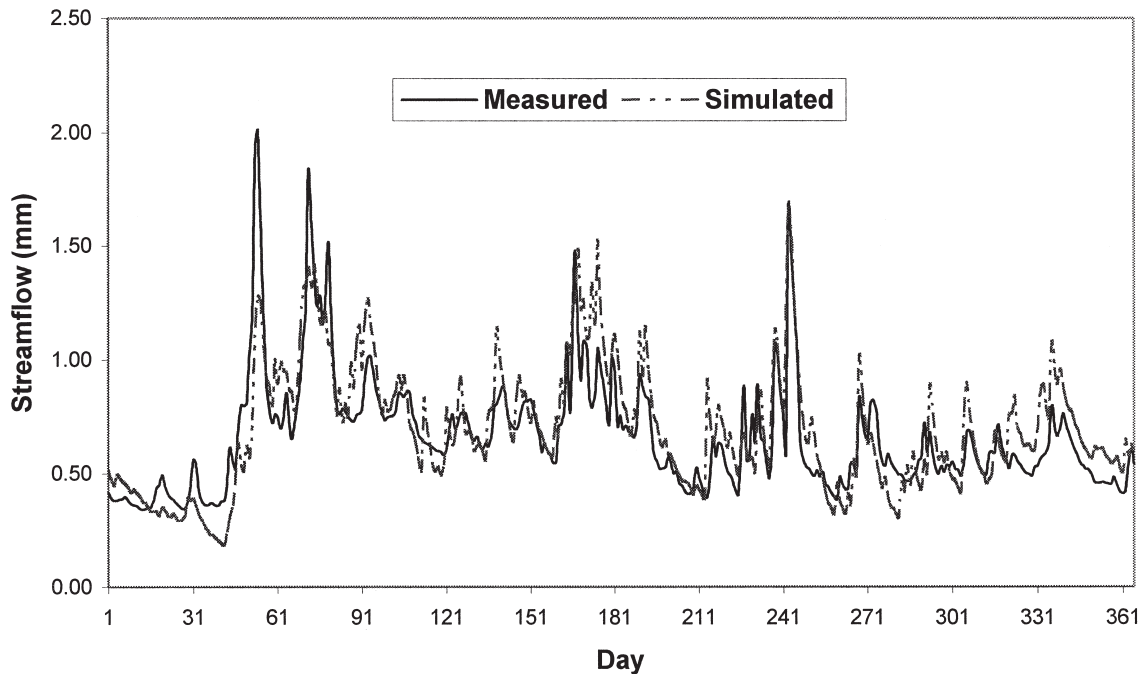

Figure 3. Measured Versus Simulated Average Daily Flow Values During 1981 to 1990 for Watershed 7060006 (Maquoketa River Watershed).
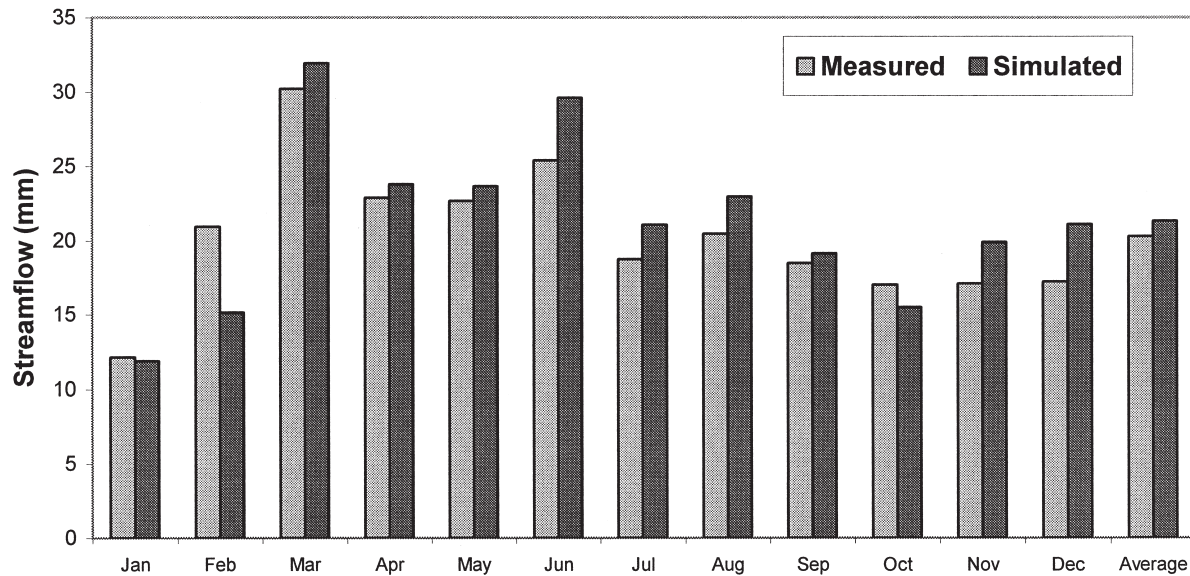
Figure 4. Measured Versus Simulated Average Monthly Flow Values During
1981 to 1990 for Watershed 7060006 (Maquoketa River Watershed).

specified, AVSWAT automatically delineates the sub-watersheds. Different minimum threshold drainage areas were used for each of the four watersheds to generate different numbers of subwatersheds (Table 3). The individual subwatershed areas varied in size within each subdivided watershed, as shown by the examples of the three subdivision configurations for Watershed 2 in Figure 5. Variable subwatershed sizes were also used in the studies performed by Bingner *et al.* (1997) and FitzHugh and MacKay (2000).

TABLE 3. Minimum Subwatershed Areas (km^2)
Simulated for Each Level of Subwatershed
Subdivision for the Four Different Watersheds.

Number of Watersheds	Watershed			
	1	2	3	4
3	-	1,200	2,100	2,000
5	120	-	-	-
9	-	-	580	1,270
11	85	245	-	-
15	-	-	-	1,150
17	55	150	340	-
23	-	-	-	440
27	35	120	225	-
35	26	-	-	270
37	-	95	160	-
47	20	58	120	-
53	17	-	-	-

The subwatersheds were further subdivided into HRUs following each subdivision of a watershed. The creation of multiple HRUs within each subwatershed was a two-step process. First, the land use categories required for each of the four watershed simulations were determined, and then the different soil types that were associated with each land use were selected. One HRU was created for each unique combination of land use and soil. User specified land cover and soil area thresholds can be applied that limit the number of HRUs in each subwatershed. For example, if the threshold level for land use is specified to be 10 percent, then the land uses that cover less than 10 percent of the subwatershed area will be eliminated. After the elimination process, the area of the remaining land uses is reapportioned so that 100 percent of the land area in the subwatershed is modeled. In this study, the threshold levels for land use and soil were set at 0 percent, which allowed all soil types and land uses within each subwatershed to be included in the simulations. The spatial locations of each HRU were not simulated; instead, each HRU simply represented a certain percentage of land use and soil type within a subwatershed. Terrain parameters (slope and slope length) were also assumed to be identical for all HRUs within a given subwatershed, except for the channel length parameter that was used to compute the time to concentration, which varies with the size of the HRU.

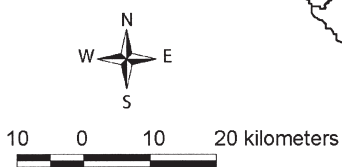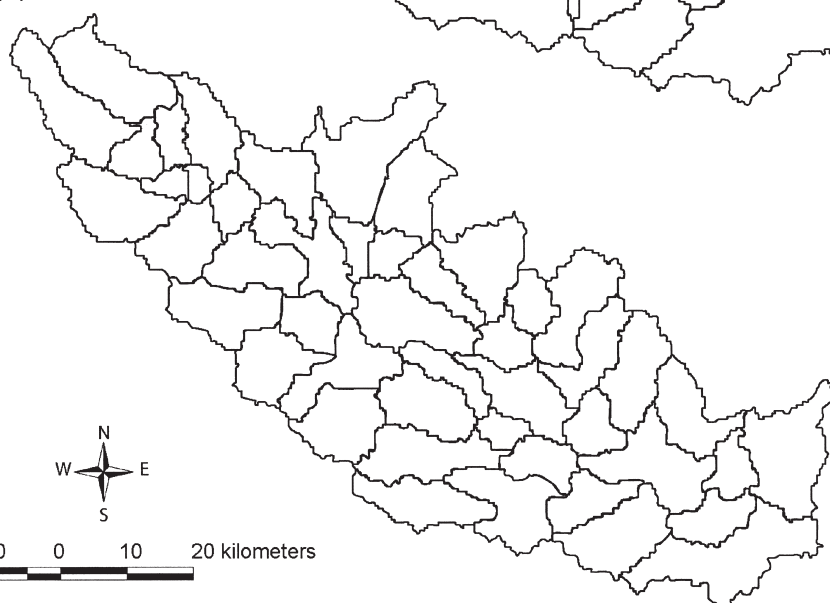(a) 3 subwatersheds
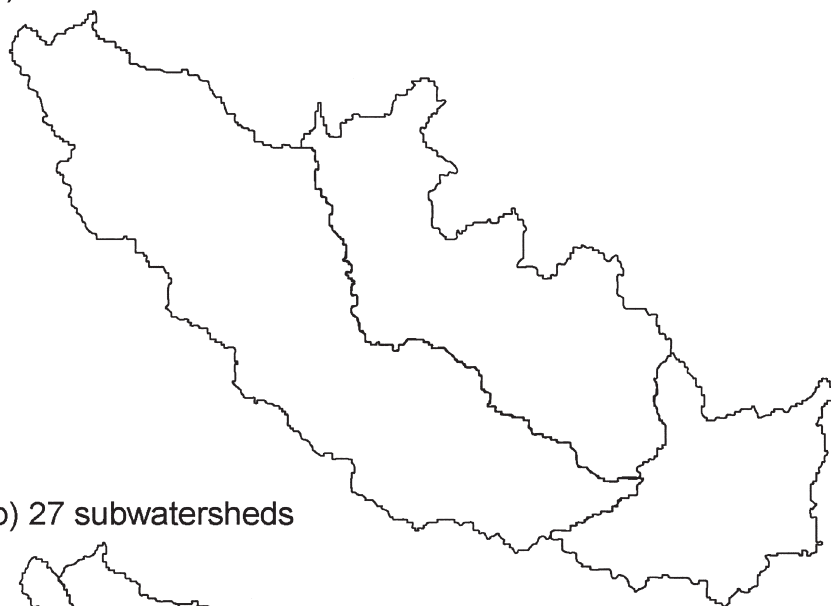
(b) 27 subwatersheds

(c) 47 subwatersheds

N
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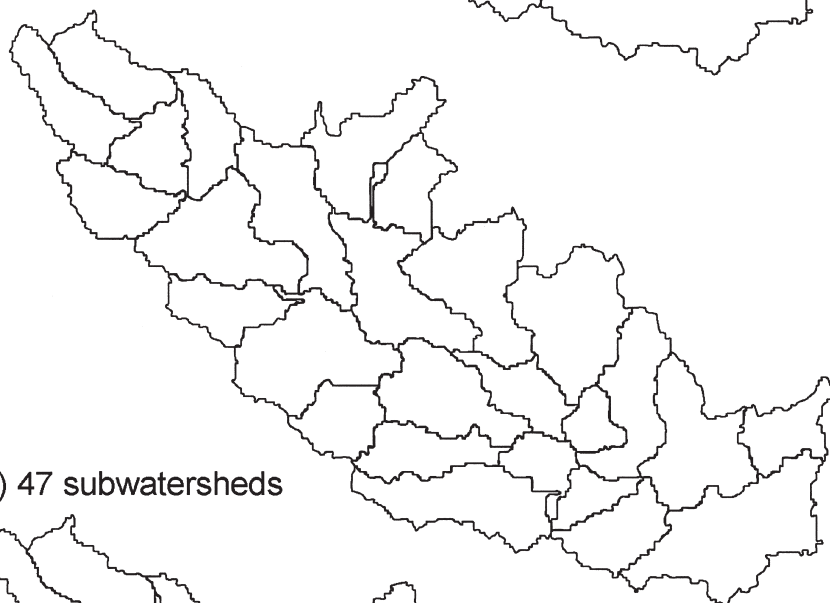
10   0   10   20 kilometers

Figure 5. Subwatershed Configurations for Watershed 2 When Subdivided by
(a) Three Subwatersheds, (b) 27 Subwatersheds, and (c) 47 Subwatersheds.

RESULTS AND DISCUSSION

Predicted annual average runoff and streamflow, sediment yield, and nutrient loadings are reported using several sets of subwatershed delineations for each of the four watersheds. Five to seven different configurations, ranging from one to three subwatersheds at the coarsest level to 35 to 53 subwatersheds for the most refined scenarios, were simulated for Watersheds 1 through 4 (Table 3). The total number of HRUs simulated for the four watersheds remained nearly constant across the different subwatershed delineations because the land use and soil thresholds were set at 0 percent. Graphical results are shown first for Watershed 1 and then in combined form for Watersheds 2 through 4 for the flow and sediment results, to accommodate the different response characteristics that were predicted for Watershed 1. The results for all four watersheds are shown together for the nitrate and mineral P responses.

Streamflow

Figure 6 shows the predicted average annual streamflow discharges that occurred at the outlet of Watershed 1 in response to different levels of simulated subwatersheds. The streamflow increased by less than 7 percent between the coarsest and finest watershed delineations, indicating that SWAT's streamflow component was relatively insensitive to changes in the number of subwatersheds. The area weighted mean curve number was virtually constant across all seven subwatershed scenarios for Watershed 1 (this resulted in little variation in the total estimated surface runoff between the subwatershed configurations). Thus, the slight trend of increasing streamflow shown in Figure 6 resulted because of other factors. Further analysis of the Watershed 1 simulation revealed that transmission gains from shallow ground water (alluvial channels) to the main stream channels tended to increase as the subwatersheds decreased in size, while the corresponding transmission losses to shallow ground water declined. This phenomenon resulted in the net increase in streamflow shown in Figure 6.

The average annual streamflow results predicted for the other three watershed outlets also remained nearly constant as the number of simulated subwatersheds increased (Figure 7). The average fluctuation between the highest and lowest streamflows for the different subwatershed delineation levels was only 4 percent among the three other watersheds. The largest streamflow fluctuations occurred for Watershed 3 (Figure 7), but these were still relatively small

and smoothed out at a subdivision level of 17 subwatersheds. The slight increases in streamflow for Watersheds 2 to 4 were again due to the "transmission effect" as described above. These relatively stable streamflow predictions are consistent with the results reported by Bingner *et al.* (1997) and FitzHugh and Mackay (2000), who found that streamflow was relatively unaffected by subwatershed size for the watersheds they studied.
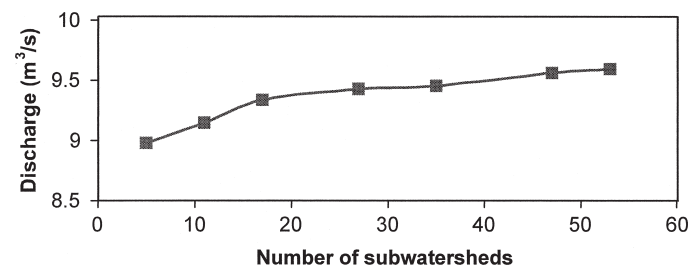

Figure 6. Average Annual Streamflow Discharges at the Outlet of Watershed 1 as a Function of Total Subwatersheds.
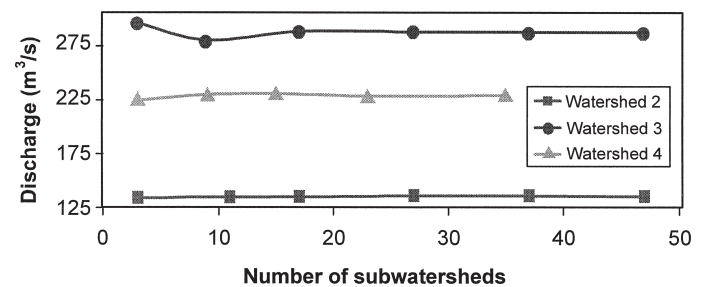

Figure 7. Average Annual Streamflow Discharges at the Outlets of Watersheds 2 Through 4 as a Function of Total Subwatersheds.

The implication of the flow results for Watersheds 1 to 4 is that the runoff generating processes simulated in SWAT are much more important than the size of the subwatersheds, in regards to the overall impact on the flow rates predicted by the model. The key factor affecting streamflow are the characteristics of the HRUs. Surface and subsurface runoff are generated at the HRU level. Thus, HRU modifications that affect the distribution of simulated land use, soils, and other landscape characteristics will have the greatest impact on the predicted streamflow rates. In addition, lateral and ground water flow are assumed to reach the subbasin stream outlet before being routed to the next subwatershed reach, which effectively eliminates the effects of simulation processes dependent on subwatershed size. The only flow processes that are affected by subwatershed size are flow losses in the channels, which are nonlinear in nature, and

any losses via evaporation that occur from ponds or wetlands that are linear adjustments. These loss pathways are relatively minor compared to other processes simulated in the model.

Sediment Yields

Figure 8 shows the trend in predicted average annual sediment yield for Watershed 1 as a function of the number of simulated subwatersheds. In general, the predicted sediment yield increased at a much greater rate as compared to the streamflow results, in response to increasing numbers of subwatersheds. A sharp increase in sediment yield occurred when the number of subwatersheds was increased from 1 to 17, but the rate of increase slowed significantly for delineations that exceeded 17 subwatersheds. These results indicate that there is a threshold or critical level of subwatershed scaling for predicting sediment yields for Watershed 1, and that this threshold level occurs at a delineation of 17 subwatersheds. Subdividing Watershed 1 with greater than 17 subwatersheds does not provide a clear improvement in the sediment yield predictions, but using fewer than 17 subwatersheds could result in less stable results.
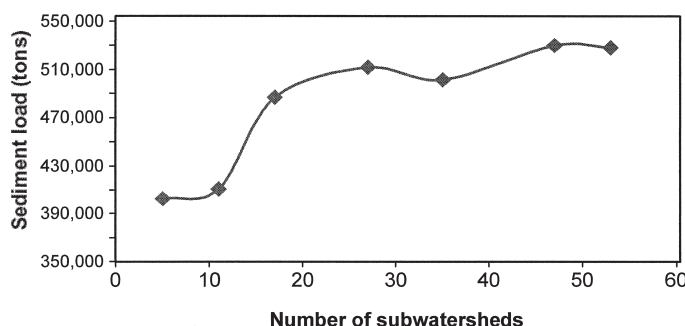

Figure 8. Effect of Subwatershed Delineation on Average Annual Sediment Yield for Watershed 1.

The total sediment load predicted by SWAT for a watershed is affected by both the MUSLE, which is used for estimating subwatershed loadings, and also the sediment routing via channels that is based on the stream power (velocity). The MUSLE equation has an implicit delivery ratio built into it that is a function of the peak runoff rate, which in turn is a function of the drainage area. The sediment routing is a function of channel length and other channel dimensions that are affected by the subwatershed size. Both algorithms are nonlinear and will be affected differently by subwatershed size and channel lengths. Further investigation was performed as a function of

subwatershed delineations to assess the impacts on total watershed sediment load predictions of: (1) the overland slope and slope length components used in the MUSLE equation and, (2) the deposition and degradation components incorporated in the sediment routing process.

The overland slope and slope length delineated for a subwatershed can change as the size of the subwatershed changes. Slope and length of slope (LS-factor) parameters used in the calculation of the MUSLE topographic factor are sensitive factors that can greatly affect the SWAT sediment yield predictions. However, further analysis of Watershed 1 revealed that relatively small variations of slope and slope length, averaged by area across all subwatersheds, occurred among different levels of subwatershed delineations (Figure 9). The LS-factor and the corresponding predicted sediment yields were not sensitive to these small changes.
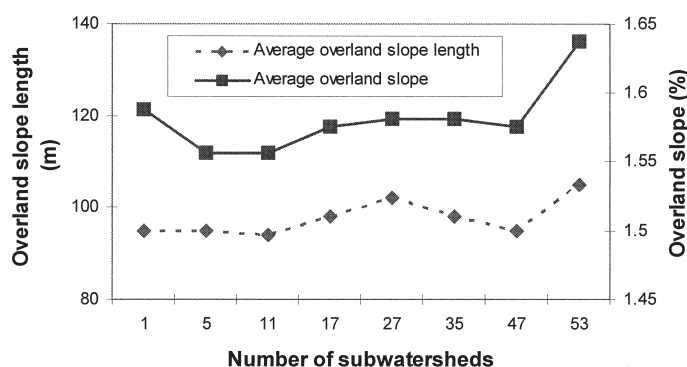

Figure 9. Effect of Subdivision on Overland Slope and Slope Length for Watershed 1.

The deposition and degradation components used in the algorithms to simulate sediment routing are a second set of sensitive factors that can strongly influence the SWAT sediment yield predictions. As subwatershed size increases, drainage density (total channel length divided by drainage area) decreases because of simplifications in describing the watershed. When drainage density is reduced, previously defined channels and their contributing areas are replaced by simplified overland flow elements that can affect the routing phenomena and decrease the accuracy of prediction. Figure 10 shows that drainage density increased as the number of subwatersheds increased. The slopes of the channels followed a similar trend (Figure 11). This increase in slope could result from a better accounting of spatial variation for elevation when smaller subwatersheds are used. Changes in channel length and slope affect the deposition (caused

by settling velocity) and degradation (see Equation 1) of sediments. After a certain level of subwatershed delineation, when all possible spatial variations due to subdivisions are introduced, further changes in the shape and size of the subwatersheds produce very little effect on the sediment yield.
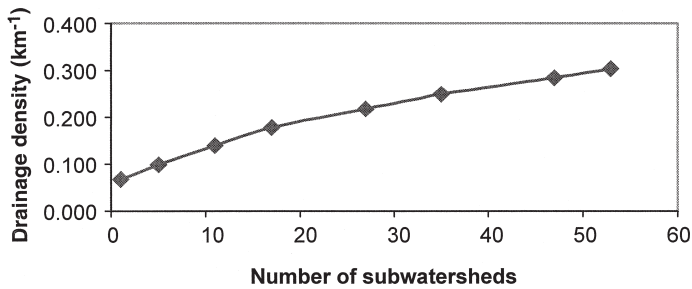

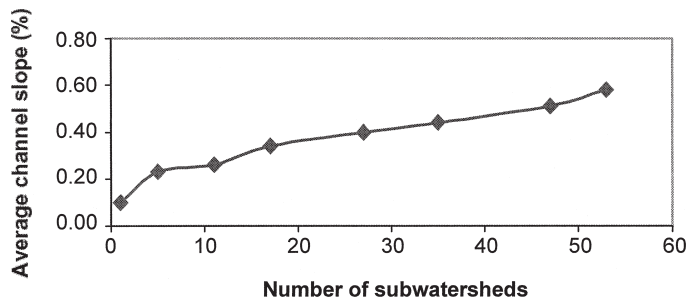Figure 10. Effect of Subdivision on Drainage Density for Watershed 1.

Figure 11. Effect of Subdivision on Average Channel Slope for Watershed 1.

Figure 12 shows the predicted average annual sediment yield trends in response to increasing numbers of subwatersheds for Watersheds 2, 3, and 4. The trends in sediment yield predictions for Watersheds 2 and 3 reinforce the concept that a threshold exists in which further subdivisions of the watersheds result in little change in sediment yield. However, a clear threshold is less discernible for Watershed 4. It was not clear why the sediment yield trends for the largest watershed exhibited a more steady state response as compared to the other three watersheds. Nevertheless, the Watershed 4 response also confirms that continued refinement of a watershed, in terms of increasing numbers of subwatersheds, will not necessarily result in improved sediment predictions.
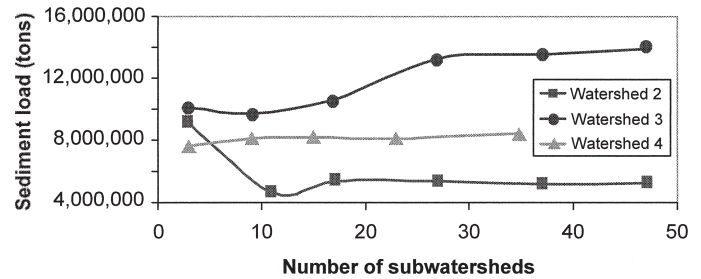

Figure 12. Effect of Subwatershed Delineation on Average Annual Sediment Yield for Watersheds 2 Through 4.

Table 4 lists the number of subwatersheds determined to be the threshold levels of subdivision for the four watersheds. The choice of 15 subwatersheds for Watershed 4 was somewhat arbitrary; selecting 9 or 23 subwatersheds would produce very similar results. At the threshold level, the minimum subwatershed drainage areas required for effective and adequate simulation of sediment yield ranged between 2 and 6 percent of the total drainage areas (with a median of 3 percent) for the four watersheds. These areas provide the upper limit of subdivision for adequate simulation of sediment yield for each watershed. Watershed subdivisions beyond these threshold subwatershed areas have little impact on sediment yield. Using subwatershed areas larger than those shown in Table 4 would result in significant variations of sediment yield predictions.

TABLE 4. Threshold Levels for Predicting Sediment Yields for Watersheds 1 Through 4.

Watershed	Total Drainage Area (ha)	Threshold Levels			
		Subwatersheds	Average Subwatershed Area (ha)	Minimum Subwatershed Area (ha)	Percent of Total Area Covered by Minimum Area
1	192,900	17	11,347	5,500	3
2	477,600	17	28,094	15,000	3
3	1,082,900	27	40,107	22,500	2
4	1,794,100	15	119,607	115,000	6

N Concentrations

The trends in predicted average annual nitrate concentrations at the outlets of all four watersheds are shown as a function of total subwatersheds in Figure 13. The nitrate losses increased at first with increasing numbers of subwatersheds, because of the previously described increasing surface and shallow ground water flows that occurred in relation to decreasing subwatershed size. The nitrate loss trends reflect the complexities of the simulated losses and transformations that are built into the SWAT nutrient routing algorithms. Thus, the predicted nitrate loss responses exhibit a clear sensitivity to subwatershed size, as opposed to the previously described streamflow trends that only have transmission losses.
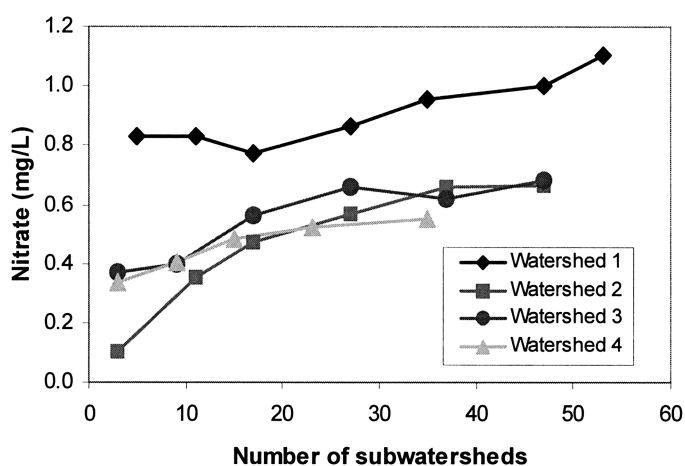

Figure 13. Average Annual Nitrate Concentrations at the Outlets of Watersheds 1 Through 4 as a Function of Increasing Numbers of Subwatersheds.

Threshold subwatershed levels were discernible for all the watersheds except Watershed 1. For Watershed 1, the nitrate concentration trends continued to increase noticeably out to the maximum number of 53 subwatersheds. Threshold subwatershed levels determined for the nitrate concentrations are listed in Table 5. A threshold level of 35 subwatersheds is suggested for Watershed 1, which is in a similar range of the thresholds determined for Watersheds 2 and 3. However, a higher level of subwatersheds for Watershed 1 can be justified based on the trends shown in Figure 13. The number of subwatersheds and associated areas for the nitrate thresholds reflect a finer resolution than those found for the sediment yields, for three out of the four watersheds.

The organic N concentrations (not shown) generally decreased as the subwatershed size was decreased for all four watersheds, which was the opposite of what was found for the NO_3-N concentrations and for sediment. The organic N loadings from the HRUs are directly proportional to the predicted sediment loadings. However, the current channel routing of organic N in SWAT is not linked to the sediment routing. Thus, the trends in organic N loss would not necessarily be expected to track those found for sediment.

P Concentrations

Figure 14 shows the trend of the predicted annual average mineral P concentrations (mg/L) at the outlets of all four watersheds as a function of decreasing subwatershed size. Contrary to the nitrate trends, the trends in the mineral P concentrations were relatively stable. The largest concentration shifts occurred between the first two subwatershed subdivisions for Watersheds 1 and 2. This implies that the transformation processes that occurred during the routing of the mineral P had only minor effects on the mineral P concentrations. The largest overall increase in mineral P concentrations was estimated for Watershed 1, which increased about 15 percent between the delineations of 5 to 53 subwatersheds. Appropriate subdivision thresholds for the four watersheds are given in Table 6. However, selecting other subwatershed configurations for Watersheds 3 and 4 would have

TABLE 5. Threshold Levels for Predicting Nitrate Losses for Watersheds 1 Through 4.

Watershed	Total Drainage Area (ha)	Threshold Levels			
		Subwatersheds	Average Subwatershed Area (ha)	Minimum Subwatershed Area (ha)	Percent of Total Area Covered by Minimum Area
1	192,900	35	5,511	2,650	1.4
2	477,600	37	17,689	9,500	2.0
3	1,082,900	27	63,700	22,500	2.1
4	1,794,100	23	78,004	44,000	2.5

minimal impacts on the predicted mineral P concentrations for those two watersheds.
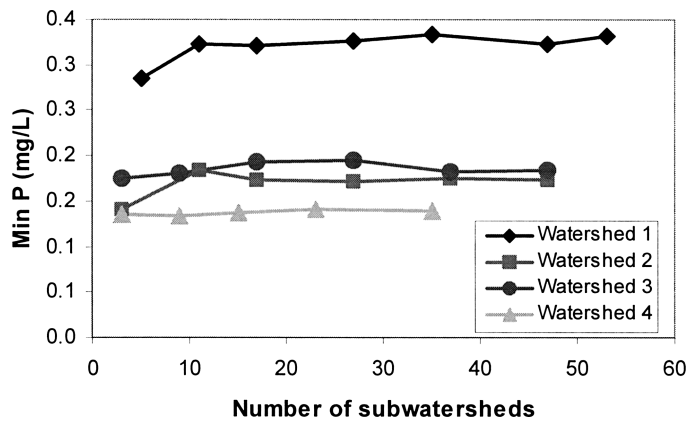

Figure 14. Average Annual Mineral Phosphorus Concentrations
at the Outlets of Watersheds 1 Through 4 as a Function
of Increasing Numbers of Subwatersheds.

The organic P trends (not shown) for the four watersheds exhibited a decreasing pattern as the number of subwatersheds increased, similar to that found for organic N but opposite of the mineral P, NO_3-N, and sediment trends. The organic P loads are again directly proportional to sediment losses from the HRUs but are not connected to the sediment in the SWAT channel routing routine, so differences between the sediment and organic P trends were not unexpected.

CONCLUSION AND RECOMMENDATIONS

It is standard practice to subdivide a watershed into smaller areas or subwatersheds for modeling purposes. A suitable method to determine an appropriate number of subwatersheds would aid users in applying models such as SWAT for a variety of watersheds. This study provides initial guidelines for determining an appropriate level of subdivision for SWAT that will efficiently and adequately simulate the sediment yield for relatively large watersheds that cover several thousand km² in area. The sensitivity of the model in predicting flow, sediment yield, N, and P as a function of subwatershed delineations, was analyzed for four watersheds in Iowa using topography (DEM), land use, soil, and climate data obtained from the same sources. The results of the analyses lead to the following conclusions.

1. Streamflow is not significantly affected by increasing the number of subwatersheds. This is because the surface runoff is directly related to the CN, and CN is not affected significantly by the size of the subwatersheds. However, there is a minor increase (4 percent on average) in streamflow due to an increase in transmission gains (subsurface flow) and to a decrease in transmission losses as subwatershed size decreases.

2. Predicted sediment yields were directly related to subwatershed size. This variation is due to the sensitivity of overland slope and slope length, channel slope, and drainage density. Changes in these parameters cause changes in sediment degradation and deposition, and, finally, to the sediment yield.

3. Large variations in the predicted sediment yields resulted during initial changes in subwatershed delineations. However, the sediment yield predictions stabilized for further refinements of subdividing the watersheds, indicating that there is a threshold level of subdivision beyond which additional accuracy in the predictions will not be gained. The threshold drainage area of the subwatersheds, at which point the predicted sediment yields stabilized, was found to range between 2 and 6 percent of the total drainage area, with a median value of 3 percent. Therefore, 3 percent of the total area is proposed as

TABLE 6. Threshold Levels for Predicting Mineral P Losses for Watersheds 1 Through 4.

| Watershed | Total Drainage Area (ha) | Threshold Levels | | | |
		Subwatersheds	Average Subwatershed Area (ha)	Minimum Subwatershed Area (ha)	Percent of Total Area Covered by Minimum Area
1	192,900	11	17,536	8,500	4.4
2	477,600	17	43,418	15,000	3.1
3	1,082,900	9	120,322	58,000	5.4
4	1,794,100	9	199,344	127,000	7.1

the smallest subwatershed size that would be considered the threshold area for adequate and efficient simulation of sediment yield for a given watershed.

4. Changes in the nitrate concentrations stabilized at higher levels of subdivision, resulting in threshold drainage areas that ranged between 1.4 and 2.5 percent of the total watershed areas. Based on these findings, it is recommended that the minimum subwatershed size be set at no smaller than 2 percent of the overall watershed area when simulating nitrate levels with SWAT for watersheds similar to those studied here.

5. Mineral P concentrations increased slightly as the number of subwatersheds were increased, resulting in a subdivision threshold of about 10 subwatersheds. This translates to subwatershed areas that are 3.1 to 7.1 percent of the overall watershed areas. Thus, it appears that a minimum subwatershed size of around 5 percent would be adequate for simulating mineral P losses.

It was also observed that organic N and P in streamflow decreased as the number of subwatersheds increased, in contrast to the opposite trends found for sediment, nitrate, and mineral P. These results are not totally unexpected because the channel routing of organic N and P are not currently linked to the sediment routing in SWAT. This fact implies that future versions of SWAT should be modified to include a direct linkage between the routing of sediment and organic N and P.

Watershed modeling studies should include a sensitivity analysis with varying subwatershed delineations similar to those described in this study. The threshold level of subdivision determined from the analysis should then be used for the actual watershed study. However, time and/or resource constraints will often preclude the ability to perform such a sensitivity analysis. As an alternative, the results from the study reported here can be utilized as a guideline to delineate subwatersheds for a watershed. Restricting the subdivision of a watershed to the threshold levels reported here would reduce input preparation efforts and subsequent computational evaluation and at the same time reduce the risk of misleading results that could occur from using a subdivision that is too coarse. The fact that different thresholds have emerged for different indicators underscores the need for SWAT users to assess which indicators have highest priority in their analyses. Finally, additional research is needed to ascertain if the results obtained here will change when using more detailed land use and soil layers than those available from the BASINS package, or for watersheds that differ greatly in size as compared to the four watersheds that were included in this study.

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